7.0 EXPOSURE ASSESSMENT

Exposure assessment is an analysis of the potential exposure pathways between the source of a chemical or physical contaminant and human or ecological receptors. A preliminary exposure assessment was presented in the CSM report prepared by the project team (MWH, 2002a). This section of the report presents a summary of the preliminary information contained in the CSM report and updates the exposure assessment based on the extensive field and laboratory work conducted since the initial assessment.

Previous sections of this report have described the current understanding of the potential for perchlorate releases from former NWIRP McGregor to impact various environmental media (i.e., surface water, groundwater, soil, sediment, or biota) within the Bosque and Leon River watersheds. The results of extensive investigations into the effects of perchlorate on various receptors were also presented. Based on these data, the updated exposure analyses presented in this section describe potential exposures of human or ecological receptors to perchlorate at the point of contact with these known or potentially impacted media. To the extent possible, the effects of these exposures are also described, either from the results of field investigations, laboratory studies, or modeling.

Information on potential exposure pathways is presented in Section 7.1. A human health exposure analysis is presented in Section 7.2. An analysis of potential exposures for ecological receptors is presented in Section 7.3.

7.1 DESCRIPTION OF POTENTIAL EXPOSURE PATHWAYS

For human or ecological exposure to a chemical contaminant from a site to occur, a complete exposure pathway between the source of the contaminant and a receptor must exist. A complete exposure pathway as defined by Risk Assessment Guidance for Superfund (RAGS) (USEPA, 1998a) consists of four essential elements, as follows:

- Source: A source of contamination and a mechanism of release.
- Medium: A receiving or transport medium (soil, sediment, groundwater, surface water, air, or food). Once released to the receiving or transport medium, transformations may occur (for example, biodegradation) that can change the chemical.
- Exposure Point: A point of potential human or ecological contact with the receiving or transport medium.
- Exposure Route: A route for the contaminant to enter the organsim, such as eating and drinking (ingestion), skin (dermal) contact, or breathing (inhalation).

If one or more of the above elements is absent, then the exposure pathway is incomplete, and no exposure can occur.

Source and Transport Media. NWIRP McGregor is a known source of perchlorate contamination. From this source, perchlorate could be released to various receiving and transport media such as surface water, groundwater, sediment, soil, or food. Erosion and runoff from former NWIRP McGregor soils that are contaminated with perchlorate, direct deposition of perchlorate-containing wastes, or interaction between surface water and contaminated shallow groundwater could potentially contaminate surface water and sediment within the Bosque and Leon River watersheds. Perchlorate can enter groundwater through migration from surface and subsurface soils, surface water, or through direct deposition of wastes into water-bearing soils. Data from this study document extensive interactions between surface water and shallow groundwater along the stream systems that originate at NWIRP McGregor (Section 5.1.3, Chapter 6), providing a pathway for any perchlorate contamination present to migrate between the surface water system and groundwater system. Irrigation of commercial and residential lawns, other garden/landscape areas, and stock ponds with perchlorate-contaminated water may transport perchlorate to soil. Additionally, this study has documented that perchlorate can be released back into the soil from plant leaves after they fall (Section 5.3.3).

Plants and animals exposed to perchlorate contamination directly from any of the transport media discussed above could themselves become transport media to higher trophic level species (including humans) via the food chain. Uptake of perchlorate by aquatic producers (e.g., phytoplankton and algae) was demonstrated to occur within surface water bodies of the Bosque and Leon River watersheds. Once absorbed by producer level receptors, there is a potential for transfer of perchlorate to consumer level receptors including aquatic invertebrates, planktivorous fish, and herbivorous aquatic birds. Additionally, leaf litter data collected from terrestrial plants during this study suggest that perchlorate could be released from fallen tree leaves. This may be viewed as an additional mechanism for perchlorate exposure to lower trophic systems. Consumer species in turn provide a means of perchlorate transfer to higher trophic level receptors including omnivorous or carnivorous fish, amphibians, mammals, and birds that may prey on the contaminated herbivores. For receptors that are located closest to an area of perchlorate contamination, those species with small foraging ranges (e.g., bullhead minnow, yellow mud turtle, red-winged blackbird) would be expected to have higher exposures to perchlorate than those species with large foraging areas (e.g., white bass, armadillo, great blue heron) because the latter tend to forage over areas of varying degrees of contamination.

Exposure Points. Exposure points exist wherever humans or ecological organisms could come into contact with potentially contaminated receiving or transport media. Examples of potential exposure points include a contaminated body of water in which a person or organism swims, a contaminated spring where people or animals drink water, or the root zone of a plant in contact with contaminated soil and groundwater. Potential exposure points vary depending on the human or ecological receptor group considered. These groups and their likely exposure points are discussed in more detail in Section 7.2 Human Exposure Analysis and Section 7.3 Ecological Exposure Analysis.

Exposure Routes. Of the three potential exposure routes presented above (ingestion, inhalation, or dermal contact), ingestion (including uptake by plants) is considered to be by far the most significant route of perchlorate exposure for both human and ecological receptors. Exposure to perchlorate via dermal contact is deemed insignificant because the high ionic charge on perchlorate inhibits transfer through the skin (Scheuplein and Bronaugh, 1983). Inhalation of gaseous phase perchlorate is considered insignificant because the vapor pressure of perchlorate salts and acid solutions is low (Allred, 1998). Although inhalation of particulate contaminants in ambient air or contaminated water as an aerosol could potentially result in minor exposure, incidental ingestion of larger particles or droplet-sized water is considered to be a much more significant exposure route. Therefore, in discussion of potential human and ecological exposure pathways to perchlorate, ingestion is considered the only realistic exposure route.

Potentially complete and incomplete exposure pathways for various human and ecological receptors are described in Section 7.2 and Section 7.3.

7.2 HUMAN EXPOSURE ANALYSIS

The updated human exposure analysis described in this section considers current and future land uses, human activities and receptors consistent with these land uses, and exposure pathways between human receptors and contaminated media based on investigations conducted during this study.

7.2.1 Land Uses

The study area includes portions of Bell, Coryell, and McClennan counties. There are rural or developed communities within each of these counties. Current land use indicates urban, pasture, range/forest, crops, and dairy waste fields (EnSafe, 1999a). Land and properties surrounding NWIRP McGregor are primarily agricultural, but little to no farming occurs in the Washita Prairie west of the South Bosque River due to calciferous soils. East of the South Bosque River are fertile, black soils that support non-irrigated row-crop farming. The City of McGregor, which adjoins the facility at the northeast corner, has a population of approximately 4,700. Land bordering the east side of NWIRP McGregor is zoned residential and land near the southern boundary supports commercial and light manufacturing operations and a university research center. Just south of the residential area is the McGregor High School. The remainder of the area is sparsely populated open farming and grazing land (EnSafe, 1999a).

Lake Waco and Lake Belton provide drinking water for nearly 500,000 citizens (Brazos River Authority, 2001b). Seeps, dug wells, and private wells supply additional sources of drinking water and/or water for irrigation or stock ponds.

Lake Waco and Lake Belton also support a variety of recreational activities including boating, swimming, and fishing. The Bosque River supports a significant recreational fishery.

7.2.2 Human Receptors

Based on the land uses described above, several potential human receptors were identified. These potential human receptors are listed in **Table 7-1**.

Table 7-1
Potential Human Receptors

Potential Human Receptor	Description
Public Water Supply Users	Individuals who use water from the public water supply. This category makes up the vast majority of potential human receptors.
Residential Users of Local Surface Water and/or Shallow Groundwater	Individuals who rely on water directly from springs, streams, or shallow groundwater within the study area instead of on the public water supply for their potable water source. This category includes a limited number of potential receptors.
Commercial/Industrial Workers	Commercial and/or industrial workers on lands formerly comprising NWIRP McGregor or in the vicinity of NWIRP McGregor within the study area. This group does not include NWIRP site workers.
Agricultural Workers	Agricultural workers within the study area
Recreational Users	Hunters, hikers, campers, fisherman, swimmers, water skiers and other recreational users within the study area.
NWIRP Vicinity Residents	Individuals residing in proximity to NWIRP McGregor and/or areas where surface water, groundwater, soil or sediment media are impacted by perchlorate.

The potential exposure media and possible exposure routes associated with each medium are described in the following subsections. **Table 7-2** lists potential human receptors and the exposure pathway elements for each receptor. The sub-sections following this table present more detailed findings for each of these receptor groups.

Table 7-2
Potential Human Receptors and Exposure Pathways

Receptor	Exposure Pathway Elements (+ means present)					Comments
	Perchlorate Source and Release	Receiving or Transport Medium	Exposure Point	Exposure Route	Complete Exposure Pathway	
Public Water Supply Users	+	+	-	+	No	Perchlorate is not detectable in the public water supply, water supply intakes, or the Lake Belton and Lake Waco intake source waters.
Residential Users of Local Surface Water and/or Shallow Groundwater	+	+	+	+	Yes	Surface water and shallow groundwater in the vicinity of NWIRP are impacted by perchlorate, but most residents within the study area are thought to be in the Public Water Supply Users category.
Commercial/Industrial Workers	+	+	-	-	No	Exposure of commercial /industrial workers is not anticipated due to the absence of points of exposure and exposure routes.
Agricultural Workers	+	+	+	+	Yes	Soil and sediment pathways are considered to be theoretically complete via incidental ingestion, but the likelihood of such an exposure occurring is thought to be extremely small.
Recreational Users	+	+	+	+	Yes	Complete pathways include the food chain and incidental ingestion of surface water, soil and sediment.
NWIRP Vicinity Residents	+	+	+	+	Yes	Complete pathways include the food chain and incidental ingestion of soil and sediment.

7.2.2.1 Public Water Supply Users

The public water supply users receptor group includes approximately 500,000 people who rely on public water from the Bosque and Leon River watersheds. This group makes up the vast majority of potential human receptors. The primary transport medium of concern for this group is surface water, specifically water from Lake Belton and Lake Waco.

Public water supply in the study area is a mix of surface water from Lakes Waco and Belton as well as limited local groundwater from city wells (Study Area Stakeholders Alliance, 1998). The City of Waco operates the Lake Waco intake structure located adjacent to the dam and serves the City of Waco and several adjacent communities (Study Area Stakeholders Alliance, 1998).

Three intake structures draw water from Lake Belton:

- City of Gatesville Intake – supplies water to the Cities of Gatesville, North Fort Hood, Coryell, Grove, Flat, Bound, Pancake, Mountain Community, and Fort Gates (City of Gatesville, personal communication, August 1999);.
- Blue Bonnet Water Supply Corporation – supplies water to the Cities of McGregor, Moody, Bruceville-Eddy, Woodway, Moffat, Pendleton, Elm Creek, and Spring Valley (Bluebonnet Water Supply Corporation, personal communication, August 1999); and
- Bell County WCID #1 – supplies water to the Cities of Belton, Nolanville, Fort Hood, Killeen, Harker Heights, and Copperas Cove (Bell County WCID, personal communication, August 1999).

Downstream of the Lake Belton Dam, the City of Temple operates a diversion and accompanying intake structure that supplies water to the Cities of Temple, Morgan's Point, Troy, and Little-River Academy (Jerry Kean, City of Temple, personal communication, August 1999).

Although the public water supplies for the Cities of Oglesby and Robinson are obtained from city wells screened in the Trinity Aquifer (Study Area Stakeholders Alliance, 1998), these water supply sources are not anticipated to be a potential source of exposure. This aquifer is a deep aquifer and is not connected to the shallow aquifer affected by contamination at NWIRP (refer to Section 6.2).

Extensive sampling during previous studies (approximately 1200 samples) have resulted in only five perchlorate detections. Sampling throughout the lakes and at the water intakes during this study demonstrated that perchlorate is not present at detectable concentrations in any of these potable water sources. Therefore, based on data collected during this study, direct human consumption of the public water supply is considered to be an incomplete pathway, and public water supply users are at no risk of perchlorate exposure from this source.

7.2.2.2 Residential Users of Local Surface Water and/or Shallow Groundwater

As discussed in **Table 7-1**, the residential users receptor group includes people who rely on water from streams, springs, or dug wells for their potable water source. The transport media of concern for this receptor group are surface water and groundwater.

Surface water potentially used for human consumption includes springs at a few residential locations and streams. Some dug wells have also been historical sources of drinking water (EnSafe, 1999a). Due to the extensive connection between the surface water and groundwater systems documented during this study, residential users of local surface water and/or shallow groundwater in the vicinity of NWIRP could potentially be exposed to perchlorate from such a water source anywhere surface water or groundwater have detectable concentrations of perchlorate. The U.S. Navy has documented the locations of perchlorate-contaminated groundwater plumes in the vicinity of NWIRP McGregor. The extent of these plumes is shown on **Plate 6**. Surface water areas that tested positive for perchlorate at any time during auto-sampling (see Section 5.1.1.2) during this study are also shown on **Plate 6**. The likelihood of potential exposure from consumption of surface water or groundwater decreases with increasing distance from NWIRP. Perchlorate was not detected (detection limit of 1 μg/L) in the Leon River or in the Middle Bosque River.

7.2.2.3 Commercial/Industrial Workers

This human receptor group includes commercial and/or industrial workers on lands formerly comprising NWIRP McGregor or in the vicinity of NWIRP McGregor within the study area (not including NWIRP site workers). This group has no known potential for contact with contaminated media, for several reasons. These reasons include the following: (1) many source areas have been remediated in some way, thereby limiting direct contact with source areas, (2) commercial and industrial workers do not work in areas with residual contamination, (3) other workers, such as construction workers, would work under an approved health and safety plan, and (4) deed restrictions exist on the use of certain properties formerly comprising NWIRP to ensure that activities are limited to those that would not result in exposure to perchlorate.

7.2.2.4 Agricultural Workers

Agricultural workers in the NWIRP area could potentially be exposure to perchlorate via incidental ingestion of soil particulates. Although the exposure pathway is technically complete for this group, the likelihood of such an exposure is thought to be extremely small. A limited amount of agricultural work is done near NWIRP and there is very little possibility that an agricultural worker could ingest enough particulates to constitute a significant exposure.

7.2.2.5 Recreational Users

Hunters, hikers, campers, fishermen, swimmers, water skiers, and other recreational users within the study area make up the recreational users receptor group. Transport media of potential concern to this group include surface water, soil, sediment, and food items such as plants or animals obtained from contaminated areas.

<u>Surface Water.</u> Because detectable concentrations of perchlorate were not found in either Lake Waco or Lake Belton during this study, recreational users of Lake Waco and Lake Belton are not considered to be susceptible to exposure via incidental ingestion while swimming in the lakes. However, incidental ingestion during swimming or wading could occur elsewhere in the watersheds where perchlorate is present at detectable

concentrations. Additionally, as with the Residential Users of Local Surface Water and/or Shallow Groundwater group, exposure could occur if recreational users consume water from perchlorate-contaminated springs or streams. **Plate 6** shows areas where perchlorate was detected in one or more surface water auto-samples (see Section 5.1.1.2) during this study.

Soil and Sediment. Any outdoor activities that involve digging into or contacting soil or sediment may result in potential incidental ingestion of particulates. This pathway is therefore technically complete for recreational users in portions of the study area contaminated by perchlorate. However, the likelihood of direct exposure from these media is extremely small. Locations that had detectable perchlorate concentrations in sediment pore water are indicated on **Plate 6**.

Food. Human receptors may also be exposed to perchlorate indirectly via consumption of plants or animals that have taken up this contaminant through ingestion of contaminated water, sediment, soil, or food sources. Laboratory studies and field sampling within the study area indicated that perchlorate is readily accumulated in plants exposed to water containing perchlorate. Therefore, recreational users who gather and consume wild vegetation near perchlorate-contaminated springs or streams could potentially be exposed to perchlorate. Based on field and lab data, the highest potential exposure to perchlorate from plants is most likely to come from leafy vegetation of plants, although modeling predicts that perchlorate should also accumulate in fruit and seeds (Section 5.3.5). This exposure source is limited to plants along streams where perchlorate is detected regularly in surface water. The likelihood that plants would contain perchlorate decreases with increasing distance from a contaminated water source. **Plate 6** indicates streams where perchlorate was detected at any time during this study, as well as locations where sampled vegetation had detectable levels of perchlorate.

Fishers and hunters who eat their game may also potentially be exposed to perchlorate through this source. Perchlorate was detected in some fish collected throughout the Bosque and Leon River watersheds during this study. Perchlorate detections in fish were sporadic, with perchlorate being detected in only some individuals at a particular location. This study found that, in fish, the greatest area of accumulation is the head, but perchlorate was also detected in some fillets. Since the fillet tissue is typically consumed by humans, consumption of fish from contaminated areas is a potential human exposure point.

Unlike plants, detections in fish were not restricted to areas with contaminated water, and there were detections in a few of the fish caught within both Lake Waco and Lake Belton. Perchlorate was detected in edible portions of fish fillets at levels as high as 1.4 ppm in sport fish (largemouth bass) and as high as 3.9 ppm in non-game fish (spotted gar). In Lake Waco there were a total of eight perchlorate detections in both fish fillets and heads (detection limit was approximately 50 ppb, higher for some species). Three of the detections were in fillets, out of 65 total fillets analyzed. The fish in which perchlorate was detected were large-mouth bass, channel catfish, and black crappie. All of these fish were of legal size and are typical sport fish. In Lake Belton there were a total of six perchlorate detections in fish fillets out of 54 fillets analyzed (detection limit was approximately 50 ppb, higher in some species). The fish in which perchlorate was detected in Lake Belton were largemouth bass, channel catfish, spotted gar, and drum. All of these fish were of legal size, although spotted gar and drum are not typically desired species for human consumption. Most of the fish collected from streams in the study area (the most perchlorate-impacted areas) were not of legal size (> 8 inches), and the streams identified to have the greatest perchlorate concentrations are not likely large enough to support fish of legal catchable size.

Although human exposure to perchlorate via consumption of fish caught in the watershed is possible, both laboratory and field data indicate that human exposure to perchlorate through this pathway in the study watersheds is unlikely. This conclusion is based on (1) where perchlorate occurs in surface water and the size of fish supported by those streams, (2) the preferential accumulation of perchlorate in rarely consumed tissue (head) rather than the fillet, and (3) the low frequency of detections in catchable fish. The data indicate that people who consume fish from Lake Waco and Lake Belton may periodically be exposed to low levels of perchlorate, but because benchmark doses have not yet been established, it is not possible to determine if the potential exposure is within acceptable limits. Locations where perchlorate was detected in the head or fillet of at least one fish are shown on **Plate 6**. Note that not all of these detections occurred in fish typically consumed by humans or in fish of legal catchable size.

Medium and large animals typically hunted by people were not tested for perchlorate during this study. However, raccoons and opossum captured near the most contaminated stream in the study area (S Creek) did not contain perchlorate in blood (detection limit of approximately 14 ppb), nor did they show signs of thyroid histology abnormalities. This study also evaluated the potential for exposure to perchlorate from consumption of beef exposed to perchlorate in the study area. Perchlorate was seldom detected in the plasma of cattle exposed to perchlorate through water, and was not detected in any of the samples of beef typically consumed by humans. These results suggest that the potential for perchlorate exposure to hunters who consume game from the study area is small. Some uncertainty in this conclusion remains, however, as mammal species typically hunted and consumed by people were not directly tested during this study.

7.2.2.6 NWIRP Vicinity Residents

The NWIRP Vicinity Residents receptor group includes individuals residing in proximity to NWIRP McGregor and/or areas where surface water, groundwater, soil, or sediment are impacted by perchlorate. This group is not intended to include people who rely on springs and shallow groundwater for their potable water source, as these people were included in the Residential Users of Surface Water and/or Shallow Groundwater group discussed in Section 7.2.2.2, but it does include people who may use the water for other purposes, including garden irrigation. In addition, people who gather and consume wild vegetation or who fish or hunt in the area were included in the Recreational Users group discussed above in Section 7.2.2.5.

Although individuals in this group could potentially be exposed to perchlorate through incidental ingestion of contaminated soil or sediment, as discussed for other receptor groups, exposure through these media is extremely unlikely. Therefore, the primary medium presenting a potential exposure to this group is food. Research performed during this study analyzed the potential for perchlorate uptake in vegetable and animal products typically consumed by humans.

Vegetation. NWIRP vicinity residents who irrigate their gardens with perchlorate-contaminated stream or well water and consume vegetation from these gardens may be exposed to perchlorate. Laboratory studies and field sampling within the study area indicated that perchlorate is readily accumulated in plants. Cucumbers, soybeans, and lettuce were included in the perchlorate uptake experiments performed in the laboratory. All were found to take up perchlorate when exposed, with the highest perchlorate concentrations taken up in lettuce. The highest exposure is likely to come from green leafy vegetation, but modeling predicts that perchlorate should also accumulate in fruit and seeds (refer to Section 5.3.5). If plant species are irrigated naturally or artificially with water containing perchlorate, uptake will occur, including uptake into edible portions of the plant. During this study, however, very few vegetable/edible plant gardens were found near water sources with detectable levels of perchlorate. Surface water sources found to have at least occasional detectable perchlorate concentrations during the extensive sampling conducted during this study are shown on **Plate 6**. The plumes of contaminated groundwater as determined by the U.S. Navy are also shown on **Plate 6**.

Animal Products. Animals typically consumed by humans potentially could uptake perchlorate from a contaminated water or food supply (Smith et al., 2001). This study evaluated the potential for exposure to perchlorate from consumption of beef derived from cattle exposed to perchlorate in the study area. These cattle had constant exposure to perchlorate in water for 14 weeks. Perchlorate was detected in the plasma of one animal but was not detected in any of the edible tissues typically consumed by humans (detection limit of 23 ppb). Direct consumption of beef from the study area therefore does not appear to represent an exposure pathway, although some uncertainty regarding this remains due to limitations in the study.

Although perchlorate in the low ppb range has recently been reported in milk intended for human consumption (outside of the NWIRP area) (Kirk et al., 2003), no commercial dairies were identified within watershed areas where perchlorate impacts were identified. Non-commercial use of milk from local cattle or goats in the study area remains an area of uncertainty. Potential exposure to perchlorate through consumption of products from other livestock (chickens, pigs, etc.) also remains an area of uncertainty.

7.3 ECOLOGICAL EXPOSURE ANALYSIS

The updated ecological exposure analysis described in this section includes an assessment of the biological resources within the study area, and an evaluation of potential exposure pathways between these resources and contaminated media.

7.3.1 Study Area Biological Resources

Biological resources consist of vegetation and wildlife in addition to ecological processes and significant ecological features of the area. A description of biological resources within the study area was presented by the project team in the CSM report (MWH, 2002a), including comprehensive lists of the vegetation and wildlife potentially occurring in the study area. Only some of the classes and species of organisms potentially inhabiting the study area were directly tested for exposure to perchlorate. These specific ecological receptors are discussed in Section 7.3.2, below.

Within the study area, there also potentially exists species listed as state and/or federally endangered, threatened, candidate, sensitive, species of concern, proposed threatened, proposed endangered, and priority for conservation and management. There could also be species identified as rare without specific listing status. Texas' special species that occur within the counties of Bell, Coryell, Falls, and/or McLennan were listed in the CSM report (MWH, 2002a, Table 6-6). These species were not specifically evaluated in this study, and the potential impacts of perchlorate on threatened and endangered species is an area of uncertainty. Although studies conducted on avian and mammalian species indicate that species inhabiting the study area are at low risk for population level declines related to perchlorate exposure and/or toxicity, none of the species examined were listed as threatened or endangered by the US Fish and Wildlife Service. Therefore uncertainty remains as to potential individual injury or population declines among any of these species inhabiting or migrating through the study area which may be subsequently exposed to perchlorate. Due to uncertainty about the occurrence of threatened and/or endangered species within the study area and a lack of perchlorate-specific toxicity data pertaining to these species potentially occurring within the study area, no definitive assessment of the implications of perchlorate on threatened or endangered species can be derived from the results of this study.

7.3.2 Ecological Receptors

The CSM report (MWH, 2002a) indicated that potential for perchlorate exposure, however remote, exists for all species present within the riparian habitat. However, actual exposures will vary significantly between feeding guilds and individual species depending upon the manner in which they interact with individual components of the watersheds. This study focused on filling high priority data gaps necessary to provide a more detailed evaluation of the potentially complete and incomplete exposure pathways for broad categories of ecological receptors.

Ecological receptor groups tested for potential exposure to perchlorate included aquatic and terrestrial plants, fish, frogs, birds, and small, medium, and large mammals. For most of the potential receptors, those that are located nearest to areas impacted by perchlorate appear to have the highest exposure to perchlorate. Fish were demonstrated to be one exception to this rule, as detectable concentrations of perchlorate were found in some fish in areas with no detectable perchlorate in the water at the time of collection (detection limit in water of 1 ppb), and some fish that were collected from contaminated water had no detectable concentrations of perchlorate (detection limit in fish of approximately 50 ppb). Each of the ecological receptor groups studied are discussed in the following subsections.

7.3.2.1 Plants

Sampling of plants in and near perchlorate-contaminated streams in the study area indicate that plants near these streams may take up perchlorate. Findings pertaining to exposure of aquatic and terrestrial plants and results from modeling of perchlorate uptake in plants are discussed in the subsections below.

7.3.2.1.1 Aquatic Plants

This study found that in all streams in which perchlorate was detected, the two aquatic plant species (smartweed and water cress) present in the offsite area were correspondingly found to have detectable concentrations of perchlorate. In general, good linear correlation was found between water concentrations and plant concentrations, indicating that surface water provides a complete and significant pathway for exposure of aquatic plants to perchlorate. Concentration factors for perchlorate in aquatic plants were in the range of 100 to 300. Perchlorate concentrations in aquatic plant species appear to exist largely in a state of pseudo-equilibrium with perchlorate concentrations in the water. Plant concentrations will often lag changes in water concentrations and may represent a better indicator of long-term exposure than water, as water concentrations can be highly variable depending on source control efficiency and precipitation. Locations where perchlorate was detected in aquatic plant tissues are shown on **Plate 6**.

7.3.2.1.2 Terrestrial Plants

Terrestrial plants are capable of perchlorate uptake if exposed to perchlorate. Trees located near contaminated surface water or contaminated groundwater were found to have perchlorate residues in their leafy vegetation. Perchlorate concentrations in terrestrial plants were more variable than in aquatic plants, probably due to the more variable nature of the source water. Most tree species obtain their water from within the vadose zone of the soil profile and not from bulk free flowing surface water. As such, changes in biogeochemistry throughout the year coupled with fluctuating water tables and water availability equate to a highly variable source contribution. In addition, potential leaching of perchlorate from leafy vegetation during precipitation events may also contribute to the large variability found. Regardless, leaf concentrations of perchlorate generally increased throughout the growing season and in general represented a higher perchlorate burden by mass than source water. Vegetative uptake of perchlorate in terrestrial species appears to be a function of both exposure concentration and length of exposure, suggesting a larger potential exposure for terrestrial plants than aquatic plants. Uptake of perchlorate by terrestrial plant species cannot be viewed as permanent sequestration. Leaf litter data suggest that perchlorate could be released once plant leaves senesce in the fall. This process may be viewed both as a mechanism of perchlorate exposure to lower trophic systems and a means of contaminant migration.

7.3.2.1.3 Plant Modeling

Simulations representing “worst-case” scenarios were run for terrestrial plants and aquatic macrophytes using perchlorate concentrations (270 ppb ± 157 ppb) measured at S

Creek. It was assumed that both terrestrial and aquatic plants were exposed to the same concentrations of perchlorate. The modeling indicates that dynamic patterns of perchlorate concentration are quite similar in terrestrial plants and aquatic macrophytes. The simulation results showed an initial increase in perchlorate concentration at the start of the growing season. As plant biomass increased, relative to perchlorate uptake, there was a small decrease in concentration. When the plants reached maximum growth, biomass remained relatively constant, uptake of perchlorate continued, and concentration also increased. At the end of the growing season, both biomass and perchlorate decreased as a result of senescence and mortality, resulting in a decrease in perchlorate concentrations within the plants.

The predicted concentrations in both the leaves and fruits increased significantly more than in the roots and stems. This was a result of the water being translocated from the root and stem compartments and sequestration of perchlorate in the leaves and fruits. The model predicted that the concentrations in both leaves and fruits continued to increase after the end of the growing season. Although there is no perchlorate accumulating in the leaves during this time of year, the amount of perchlorate decreases slightly less than the leaf biomass decreases, resulting in a higher concentration.

The model predicts that perchlorate is capable of bioaccumulation in the leaves and fruits of exposed plants. The model results are consistent with lab and field observations and suggest that there is potential for perchlorate exposure to wildlife and humans that consume exposed plants. Although parameter estimates were based on calibration with lab experimental data, direct measurements of unknown or assumed model parameters would improve the accuracy of model predictions.

7.3.2.2 Aquatic Animals

Field and laboratory studies were conducted on fish and frogs in the study area to evaluate the potential for these organisms to be exposed to perchlorate. The extent of perchlorate exposure determined by these studies is discussed in the following subsections.

7.3.2.2.1 Fish

Fish Field Survey. Perchlorate was detected sporadically in fish tissue samples from fish collected from streams and lakes in the study area, but it was detected in only some individuals and some species. Perchlorate was found more often in small insectivorous species (e.g., mosquitofish), sunfish, largemouth bass, and catfish, and often was found in fish tissues at concentrations higher than those found in the water. This difference in concentrations could be due to pathways of exposure other than the water column (e.g., food sources such as invertebrates, algae, etc), or to temporal variability in perchlorate exposure, followed by a slower decrease in fish tissues than in the water column. Plants may represent a larger exposure pathway to fish than direct water, as algae are a good food source for aquatic organisms, and bioconcentration factors in algae were determined to range from 100 to 300. Nonetheless, these findings do indicate that fish are being exposed to perchlorate and taking it up from the environment. Locations where perchlorate was detected in fish are shown on **Plate 6**.

The thyroid histopathology of fish collected from sites contaminated with perchlorate suggests that these fish were exposed to perchlorate found in these streams. The level of exposure was associated with monitoring data indicating the presence of perchlorate, although perchlorate is not the only environmental contaminant that could influence changes in thyroid histology. Because of the involvement of thyroid hormones in reproduction and development, it is possible that the ecological fitness of these fish may be affected. However, because population-level and community-level endpoints were not investigated, the relationship to higher-level effects is unclear.

Fish Laboratory Studies. Laboratory studies showed that perchlorate uptake from water was rapid in the fish species studied, reaching steady state within a matter of days. Perchlorate elimination was also relatively rapid, but there was a large amount of inter-individual variation in elimination rates. In particular, after 20 days of depuration, perchlorate was still detected in some individuals, but not in others. If perchlorate exposure in the field is highly variable, with perchlorate spikes being followed by rapid drops in water concentrations, this high inter-individual variability in elimination may contribute to the findings from field-collected fish (i.e., perchlorate found in only some individuals, and at concentrations greater than in the water). Laboratory studies also indicated that perchlorate did not bioconcentrate in mosquitofish or channel catfish. However, these laboratory studies were conducted at extreme perchlorate concentrations (100 ppm). These laboratory studies indicate that if inter-individual variation in perchlorate elimination and temporal variation in perchlorate water concentrations are the basis for the patterns seen in the field, then the spikes in concentrations of perchlorate in the water would have to be at least 10 times the concentrations seen in the fish tissues. Finally, perchlorate uptake and elimination rates vary with species and tissue examined. The greatest concentrations of perchlorate are typically found in the head.

Fish Modeling. A "worst-case" scenario was simulated, in which individual catfish were exposed to the highest measured field perchlorate water concentrations (540 ppb in S Creek) until their tissues reached equilibrium. Most tissue compartments took approximately 120 hours to equilibrate, with the gill and thyroid compartment taking 250 and 500 hours, respectively. If we assume that 540 ppb is the highest level any fish is exposed to, then all measured field tissue concentrations should be less than or equal to those simulated. The highest measured muscle concentration, based on tissue wet weight, was 60 ppb. Simulated muscle concentrations were ~150 ppb. Since thyroid tissue cannot be collected in fish, the head was used as an approximate measure. Field measurements had a high wet weight concentration of 850 ppb compared to a mean simulated thyroid concentration of 880 ± 120 ppb (mean ± 95% CI) after 500 hours. The thyroid concentration data were then used in the hormone secretion model to determine the level of hormone inhibition. Perchlorate inhibition was initiated after 1000 hours to allow the hormone compartments to reach steady-state prior to exposure. T3 hormone levels decreased 18.7-22% and T4 levels decreased 56.5%.

The rapid and substantial decrease in hormone levels should be viewed cautiously. We cannot fully characterize the system without the data necessary to determine a T_3

inhibition term. We took a conservative approach in assuming the inhibition term for T_3. It may be that T_3 levels do not decrease that much (behave similarly to T_4), but that is a source of uncertainty. At present, the simulated results are only a "best guess" and should not be viewed as definitive. It is also important to note that the stream (S Creek) used in this "worst case" simulation is not large enough to support fish of legal catchable size (fish that could be consumed by humans).

7.3.2.2.2 Frogs

Studies on the thyroid histology of native frogs indicate that there is a statistically significant positive relationship between thyroid follicle cell height in adult frogs and perchlorate content of surface water collected from six sites in the Lake Waco watershed. However, the relationship explains less than 40% of the variation in thyroid follicle cell height across the 86 animals examined. Although the relationship suggests that perchlorate might contribute to the statistically greater follicle cell height in frogs from the South Bosque and Harris Creek, we did not find evidence for colloid depletion in frogs from these sites. Under laboratory conditions, perchlorate exposure results in marked follicle cell hypertrophy and colloid depletion. Recent evidence suggests that similar histological changes occur in developing frogs exposed to relatively high concentrations of perchlorate (10 mg/L) in East Texas (Carr et al., 2003). However, such high part-per-million perchlorate concentrations as observed in East Texas were not observed at any of the NWIRP-McGregor sites studied. Furthermore, changes in follicle cell height may be caused by any environmental condition that a) stimulates TSH secretion, or b) inhibits thyroid hormone secretion and thereby results indirectly in elevated TSH secretion. Because the statistically significant increase in follicle cell height was not observed with a coincident depletion of colloid, we cannot say with certainty that the changes resulted from perchlorate exposure. Data from Goleman et al. (2003) also indicate that adult frogs are much less sensitive to perchlorate than are immature stages. Specifically, adult African clawed frogs, *Xenopus laevis*, show no alterations in thyroid histology after 10-week exposure to part-per-million concentrations of perchlorate. These data suggest a marked reduction in sensitivity of adult frogs to perchlorate compared to developing frogs. Taken together, the lack of evidence for colloid depletion and the observed lack of adult sensitivity to perchlorate suggest uncertainties regarding the precise causative agent(s) at Harris Creek and the South Bosque River that caused the observed changes in thyroid histology.

We found no evidence to suggest that surface water collected from any of the study sites contained sufficient perchlorate to alter thyroid function in the frog metamorphosis assay during the 38-day exposure of *X. laevis* tadpoles. If perchlorate levels were sufficient to alter thyroid activity, we would have expected that animals exposed would have exhibited either delayed metamorphosis or would not have completed metamorphosis, and would have mortality as low as that observed in the controls. Control animals in this study exhibited low mortality (3%), and the percent completing metamorphosis was 90%. The only water samples (sites along Harris Creek, the South Bosque, and Station Creek) in which metamorphosis was delayed also caused considerable mortality, suggesting that the slower rate of metamorphosis was the result of toxicity related to one or more water contaminants. None of the water samples contained perchlorate concentrations that would have been expected to produce mortality. In *X. laevis*, the concentration of ammonium perchlorate lethal to 50% of test animals (LC_{50}) is 510 mg perchlorate/L (Goleman et al., 2002a). Thus, our data suggest that mortality and reduced metamorphosis in the sites along Harris Creek, the South Bosque River, and Station Creek are due to the toxic effects of an as yet unidentified factor(s) in these water samples, or to the synergistic effect of perchlorate and another contaminant(s).

In frogs, sex determination is generally believed to be genetic. Genetic sex generally determines the phenotype of the gonadal tissue, producing ovaries in genetic females and testes in genetic males, but there are many reports of frogs with mixed phenotype, i.e. exhibiting gonads with mixed female/male characteristics (intersex gonads). There is evidence that aquatic contaminants, including perchlorate, can alter the gonadal phenotype in *X. laevis*. Chronic exposures to perchlorate at 60 μg perchlorate/L and 14,000 μg perchlorate/L during larval development can result in altered phenotypic sex ratios (more tadpoles with phenotypic female gonads, Goleman et al., 2002b). We did not observe any evidence of intersexual gonads in any of the field-collected *Acris crepitans* or laboratory reared *X. laevis* exposed to surface water samples collected from the study area. Furthermore, male and female frogs were collected at most sites in the study area. The site with the greatest mean perchlorate concentration (S Creek) tended to have more females, but we were only able to collect eighteen animals total at this site. A chi-square analysis revealed that this ratio was not statistically different from 50:50, probably because of the small sample size. Although there was a trend toward more female X. laevis reared in water from Station Creek, mortality in this group was 55%, and the animals that died prematurely could not be identified with respect to gonadal sex as they had not yet reached stage 66, the earliest stage required for phenotypic sex identification.

7.3.2.2.3 Benthic Organisms

Benthic organisms were not directly tested for exposure to perchlorate during this study. However, sampling of sediment pore water constituents for perchlorate was conducted both in streams and in the delta areas of the lakes. Benthic species could potentially be exposed to perchlorate by direct ingestion of sediment. Benthic flora may accumulate perchlorate through root uptake and transfer contamination to consumer species.

The results of sediment pore water sampling indicate that there appears to be a low probability of exposure to these benthic species in the delta areas of Lake Belton and Lake Waco, as all perchlorate concentrations in sediment pore water samples collected in these areas were below the detection limit. However, sediment pore water farther upstream in the watershed did have detectable levels of perchlorate (refer to Section 5.2.1). Benthic species in these areas would be exposed to perchlorate.

7.3.2.3 Terrestrial Animals/Birds

Small and medium mammals and birds were collected from the study area near streams and springs known to be contaminated with perchlorate. Tissues from these animals were tested to determine whether they were exposed to perchlorate. Laboratory studies and modeling were also conducted to better understand the nature of perchlorate exposure in these organisms. Potential exposures to these organisms are discussed in the following subsections.

7.3.2.3.1 Small Mammals and Birds

This study demonstrated that animals and birds in affected areas can be exposed to perchlorate either directly from drinking contaminated stream water or indirectly by consuming plants that have been exposed to perchlorate. Laboratory studies (Thuett et al., 2002) indicate the highest potential exposure levels near NWIRP may be sufficient to cause thyroid histopathological impacts in small mammals. These conclusions are based on information contained in Section 5.5.1. However, there is uncertainty regarding whether such histopathological impacts would have any direct relevance to adverse effects on individual organisms or populations of small mammals or birds present within the study area.

Field and Laboratory Studies. Small mammals and birds inhabiting portions of the study area are being exposed to perchlorate as indicated by tissue concentrations. It is likely that the exposure occurs through consumption of perchlorate-contaminated water and food. In general, the concentration of perchlorate in tissues of small mammals follows a perchlorate concentration gradient across the different sampling locations. Further evidence of variation in perchlorate exposure among sites was indicated by significant differences in quantifiable perchlorate concentrations in kidney and liver samples among small mammals. Exposure risk in small mammals appears to be at expected levels or greater at all sites except Harris Creek at Highway 84 (as measured by the number of quantifiable perchlorate hits in kidney and/or liver samples, see Section 5.5.1.1.3). Overall, the highest concentrations of perchlorate in small mammals were detected in animals collected from the following sites: Station Creek at Highway 107 (T23), the unnamed tributary near the wastewater treatment plant at Highway 317, the spring on Oglesby Road, and the spring-fed stream on the Hollan property. Note, however, that only a few animals were captured and analyzed from the spring on Oglesby Road and the spring-fed stream on the Hollan property. Small mammals at Harris Creek at Highway 84 generally had low perchlorate concentrations although their capture location was only about 200 to 400 meters from the spring on Oglesby Road and the spring-fed stream on the Hollan property. However, the exposure of Harris Creek animals may have been minimized by dilution of perchlorate from Harris Creek, the main tributary that received water flow from the spring on Oglesby Road, and the spring-fed stream on the Hollan property.

Exposure to birds was essentially measured at one site only (near the spring on Oglesby Road). Concentrations of perchlorate in these birds were consistently high and all birds had measurable concentrations of perchlorate in kidney samples. Migratory birds (doves) collected early-on in the study from a location near the spring on Oglesby Road had no perchlorate in their tissues. Uncertainty remains regarding the potential effect of perchlorate on piscivorous birds inhabiting or utilizing perchlorate-impacted sites within portions of the study area. While perchlorate was detected in numerous small fish species collected from several water bodies throughout the study area, most residues were detected in fish from tributaries rather than Lakes Waco and Belton. Also, piscivorous birds were rarely observed in tributaries, and likely utilized lake and pond environments as their primary foraging areas. Although little information is available on trophic or food chain transfer of perchlorate, based on its water solubility, the relative lack of tissue bioaccumulation in the species studied, and its rapid excretion, perchlorate would not be expected to accumulate to toxic levels in piscivorous birds. However, no data were generated during this study to completely rule out exposure to elevated and potentially harmful concentrations of perchlorate among piscivores.

Assuming that a larger sample of small mammals would have shown similar results, the likelihood of exposure to perchlorate at the spring on Oglesby Road and the spring-fed stream on the Hollan property is considered high for wildlife in this area.

Given concentrations of perchlorate measured in birds and small mammals from different sampling locations within the study area and the observed effects of perchlorate in the laboratory dosing studies on deer mice and prairie voles, it appears that field exposures are occurring at levels sufficient to cause thyroid histology impacts and plasma hormone concentrations. This conclusion is especially true for animals inhabiting the spring on Oglesby Road, the spring-fed stream on the Hollan property, Station Creek at Highway 107 (T23), and the unnamed tributary near the wastewater treatment plant at Highway 317. To a lesser extent, the same holds true for Harris Creek at Highway 84, although overall concentrations of perchlorate are lower in those animals. However, there is uncertainty regarding whether such histopathological impacts would have any direct relevance to adverse effects on individual organisms or populations of small mammals or birds present within the study area.

Uncertainty in these results includes low sample numbers from many of the sites. This result stems largely from a general lack of habitat at many of the sites, resulting in low capture success of small mammals and birds during different times of the year. The best small mammal trapping success occurred at Harris Creek at Highway 84, in a small pocket of heavy grass that supported a very localized, but dense, population of rodents. This condition was quite rare, however, with most of the trapping sites consisting of over-grazed, sparsely vegetated areas along creeks and drainages. Therefore, it is somewhat difficult to make firm conclusions about perchlorate exposure across all sites. When taken as a whole, however, animals were collected from along drainages known to originate on NWIRP, or from along groundwater springs with known perchlorate contamination, and these animals are being exposed to perchlorate as indicated by tissue residues.

<u>Small Mammals and Birds Modeling.</u> Worst-case exposure simulations were run for small mammal and bird populations using data from S Creek as a means of establishing an upper bound for perchlorate exposure. We assumed that small mammals and birds obtained their food and drinking water solely from this single area.

The simulation output showed that the concentration reached equilibrium as the result of a balance between ingested and excreted perchlorate. The process of ingesting and excreting perchlorate also explains the oscillation in each tissue compartment. There was an increase in tissue perchlorate levels caused by ingestion of contaminated food items during the day and a decrease resulting from excretion through urine and feces. In birds, it was predicted that perchlorate could be transferred from a female to her eggs.

The model predicts significant increases in perchlorate concentrations in all modeled organ and tissue compartments for the S Creek area. These increases did not, however, translate to reduced T_3 and T_4 secretion rates or lower T_3 and T_4 concentrations in model compartments. Although parameter estimates are based on literature values, conservative assumptions were made in their estimation: 1) high transport rates from the liver to the blood, and 2) low elimination rates from the gut. These simulations are only preliminary, but with the current parameter set, additional simulation experiments showed reduced thyroid activity only with order-of-magnitude greater perchlorate concentrations than those found in S Creek.

In birds, the predicted concentrations in eggs as a result of maternal transfer are within the same range as the predicted concentrations in the adult thyroid compartment, although the actual effects of this conclusion are unknown at this time.

7.3.2.3.2 Medium Mammals and Large Mammals

Perchlorate was not detected in medium-sized mammals. Raccoons and opossum captured near the most contaminated stream in the study area (S Creek) did not contain perchlorate in blood (detection limit around 14 ppb), nor did they show signs of thyroid histology abnormalities. Thyroid hormone levels in medium-sized mammals captured near contaminated streams in the study area appeared normal, consistent with residue and thyroid histology data. Perchlorate exposure (approximately 25 ppb) to large mammals (cattle) in the study area did not adversely affect thyroid hormones.

7.3.3 Limitations

Limited site access throughout the study may have prevented the determination and assessment of areas potentially containing significantly greater concentrations of and larger spatial distributions of perchlorate. Therefore, the possibility exists, although considered remote, that areas of greater perchlorate contamination or impacts than the studies conducted and presented in this report indicate exist within the study area. Furthermore, the degraded or diminished habitat (e.g. overgrazed pastures) available for investigation on many of the study sites may not accurately reflect the species composition or abundance in other areas which may also be contaminated with perchlorate. Therefore, uncertainty exists surrounding the potential for perchlorate to impact individuals, populations, or species inhabiting inaccessible locations.